Comments on Correction and Adjustment Magnets in the Tevatron

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1 Introduction

Recently we have been asked to attend some of the review rehearsals, specification reviews, and so on, relating to the Run-II program. During the most recent of these – a fine presentation of the BTeV plan – one of us (Don) realized that the work of a quarter of a century ago on the design of corrector systems was unfamiliar to the speakers. A couple of years ago, we both became aware that various correctors were running outside of the design range, so we feel that a note on this subject might be useful.

The device now known as the Tevatron started life as the Energy Doubler and was represented by a number of design reports starting in 1972 and ending up with the document entitled "A Report on the Design of the Fermi National Accelerator Laboratory Superconducting Accelerator" dated May 1979 and edited by F. T. Cole, M. R. Donaldson, D. A. Edwards, H. T. Edwards, and P. F. M. Koehler. In the 1979 report, there are relatively early ideas concerning the correction and adjustment system, but given the necessary emphasis on main magnets the statements in this document are too early to give a complete picture of the corrector components.

An accurate summary of the as-constructed components may be found in the 1985 paper by Helen T. Edwards[1] on pages 642–645 and we will use her data throughout these notes. The corrector magnet strengths in the spool pieces bounced around in the years 1979–1982 depending on construction imperatives that are no longer of interest. Rather, we prefer to concentrate below on the reasoning.

2 Steering Dipoles

There were two primary design considerations for these elements. First, the Main Ring had been plagued with obstructions and aperture scans were a standard routine. This consideration set the strength of the steering dipoles. Given a half-aperture of about 30 mm and a cell length of 30 m, that implies a 1 mrad deflection. At 150 GeV, the energy at which such studies would be carried out, this implies a steering strength of about 200 kG-in at maximum excitation. The design that was adopted was 181 kG-in.

Second, the steering elements must correct for alignment errors. A comparison of prediction and performance is to be found in TM-1324 dated June 1985 by one of us[2]. In that paper, the author concludes that the observed rms of 32μrad deflection required of the steering elements is consistent with prediction. That is a factor of 30 less than the full strength deflection obtainable at injection energy. Further, this verified that adequate full energy correction was assured for the specified alignment errors.

At that time, the field quality of the correctors was not considered an issue; the main magnets were the big concern. Simplicity due to the schedule and cost due to the budget were the paramount issues. A single shell random wind design was adopted, with the coil angle set to cancel the next-higher multipole permitted by symmetry. For the steerers, the coil angle was set at 60 degrees with respect to the midplane to avoid a sextupole moment.

A few days ago, we learned from John Johnstone of some measurement data on these magnets. That the field strength was 20% lower than the provisional design figure is not surprising; the random wind approach is not exactly elegant. The figure that we found interesting was b_2 at the level of 250 ± 150 in Fermilab's definition of the term. There was a concern at the level of 6 units of b_2 or so in the main dipoles. If we combine the statement from Syphers quoted above, the fact that one steering element is associated with eight main dipoles, and the numbers associated with sextupole moments, we find a 2% potential contribution to nonlinear resonance driving terms from the steerers. We would have thought that acceptable. But when we observe a significant number of these devices running close to full excitation, it is cause for alarm, as any outside-of-design-range indication should be.

3 Tune and Chromaticity Elements

The other magnets in the first spool package are the quadrupoles and sextupoles for tune and chromaticity manipulation. We had not heard much on these in the way of lack of performance and so forth. The design principle on this subject that we would like to emphasize is a near obsession with azimuthal harmonic content, in order that the parameter that should be manipulated does not change others as well. We will return to this subject when we get to the second spool package skew quadrupole elements below.

(As a personal admission by one of us, namely Don, the best piece of linear optics that I did was forty years ago for the Cornell 10 GeV electron synchrotron, which still functions as the CESR injector. The worst piece of linear optics that I have done was the tune adjustment capability in that same synchrotron. I meekly accepted the statement that there was no space to install other than a few trim quadrupoles. Fortunately, the dramatic excursions in the amplitude function at injection were not discovered until long after I had departed Cornell. Unfortunately, I go back there from time to time, and get reminded.)

The tune and chromaticity adjustment elements were specified as ring-wide series circuits with excitation performance consistent with the requirements of high efficiency slow extraction and avoidance of azimuthal harmonic content. The slow extraction need is no longer present; whether or not it may eventually return is unpredictable. Also, with the addition of two interaction regions, the azimuthal harmonic description of the synchrotron has changed.

We both experienced a twinge when we heard in a meeting that a sextupole had been removed from the chromaticity circuit for another purpose. We have the impression that the circuits are subject to casual modification without review. The fact that a single nonlinear delta-function can contribute to all resonance driving terms should not be forgotten[3].

4 Transverse Coupling Elements

While the first spool packages contain steering, tune, and chromaticity adjusters, the second corrector package varies from spool to spool and contains elements required for slow extraction and skew quadrupoles for coupling compensation. The latter was considered to be particularly important due to the experience in the Main Ring where slow extraction was adversely affected due to horizontal-vertical coupling, as is documented in [4]. It was not anticipated that some of the extraction elements be later used as feed-down devices to introduce local linearities onto the unforeseen separated orbits of the Collider program.

Despite the concern about transverse coupling it was gratifying that the strong skew quadrupole circuit designed as a precaution with Main Ring history in mind required only about 4% excitation during Tevatron commissioning. Later it was found that for tune control in collider operation this circuit was running at 60% excitation of full strength. This is a clear indication of an underlying problem. It was also brought to our attention that Interaction Region modifications had removed 6 of the original 48 elements of the main skew quadrupole elements. The first observation should have been recognized as a clear indication of the emergence of a skew quadruole term in the main Tevatron dipoles over a decade ago. This was verified by magnetic measurements conducted at the Magnet Test Facility [5] that corresponding with our prediction [6] a year ago. The removal of 6 elements from a particular harmonic configuration conspired with the skew quadrupole moment in the main dipoles to produce vertical dispersion. And in addition, an *ad hoc* compensation was performed using a single strong element elsewhere in the ring which produced an even larger vertical dispersion source. These events have been documented in [7]. The strong coupling source due to deterioration of the main dipole magnets could have been compensated in large part by the original skew quadrupole circuit. However, the major change in harmonic content brought about by the removal of the 6 circuit elements produced an unsatisfactory correction system in this regard. Recent improvements to the coupling after repairs to magnets in the regions of missing correctors have confirmed the validity of the above argument.

5 Concluding Remarks

Why have we been making this rant? The design of corrector and adjustment systems is not a complex issue. We contend that the original design for the Tevatron matched requirements, as was confirmed during commissioning. As the operational requirements of the Tevatron evolve, so must the requirements of the correction system. Our comments above are intended to reinforce this advice. As the Tevatron moves forward with the BTeV design new correctors for the Interaction Region should be designed with appropriate attention to field quality as well as concern for introduction of azimuthal harmonics into the system.

Present families of tune and chromaticity correctors should be checked for harmonic content. Coupling circuits must be monitored closely as main magnet improvements are performed (e.g., smart bolts). Feed down circuits and their effects on present helices (injection and collision) as well as helices for BTeV operation need to be re-examined in this context. Finally, the configuration should be reviewed and controlled effectively in the future.

References

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[3] D. A. Edwards and M. J. Syphers, *An Introduction to the Physics of High Energy Accelerators*, Wiley, New York (1993).

[4] R. Stiening and D. A. Edwards, "Decoupling of radial and vertical betatron oscilations at high-energy in the Main Ring," Fermilab note EXP-27 (1972).

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[6] D. Edwards and M. Syphers, "Strong Transverse Coupling in the Tevatron," Fermilab note Beams-doc-501 (2003).

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